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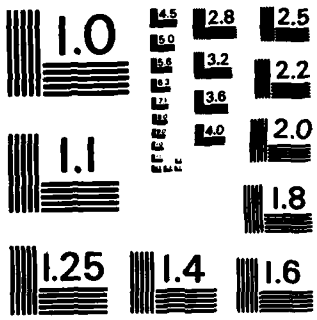

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SUN-ALIGNED POLAR CAP AURORAL ARCS

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A Model of Sun-Aligned Polar-Cap Auroral Arcs

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ABSTRACT

A model of polar cap auroral arcs is proposed under the assumption that the magnetic field reconnection occurs in the cusp region on tail field lines during northward interplanetary magnetic field (IMF) conditions. Requirements of a convection model during northward IMF are enumerated based on observations and fundamental theoretical considerations. The theta aurora can be expected to occur on the closed field lines convecting sunward in the central polar cap while the less intense polar cap arcs can occur either on closed or open field lines. The dynamo region for the polar cap arcs is required to be on closed field lines convecting tailward in the plasma sheet which is magnetically connected to the sunward convection in the central polar cap.

1. Introduction

It has been established by observations that the sun-aligned polar cap auroral arcs occur exclusively during prolonged periods ($\gtrsim 1$ hour) of northward interplanetary magnetic field (IMF), i.e., IMF $B_z > 0$ (Lassen, 1972; Berkey et al., 1976; Meng, 1981; Ismail and Meng, 1982; Frank et al., 1982). The precipitating electron flux in the polar cap arc is $\sim 10^6$ electron/cm^2-s-st which is one to two orders of magnitude higher than the polar rain level (Hardy et al., 1982). The average electron energy rises from below ~ 100 eV outside to ~ 1 keV inside the polar cap arc (Hardy et al., 1982). The differential energy spectra of precipitating electron fluxes in the polar cap arcs exhibits a characteristic peak (Meng, 1978; Hardy et al., 1982) indicating that these electrons have been accelerated by parallel electric field along field lines. Like the oval arcs, polar cap arcs are invariably associated with upward field-aligned currents in regions where $\vec{\nabla} \cdot \vec{E} < 0$ (Burke et al., 1982). Observations show that (i) polar cap arcs occur primarily on closed field lines (McDiarmid et al., 1980; Murphree and Cogger, 1981; Murphree et al., 1982; Peterson and Shelley, 1984) and (ii) polar cap arcs frequently emerge from the boundary of auroral oval (dawn or dusk side) and move toward the central polar cap. Occasionally a polar cap arc can emerge from the midnight sector and extends sunward (Frank et al., 1982). At times, a polar cap arc can last for hours (Gussenhoven et al., 1982; Webber, 1981), especially for the intense theta aurora (Frank et al., 1982). These observations, including particles, fields and optical images, suggest that polar cap arcs and oval arcs are produced by the same mechanism, i.e., by parallel electric fields accelerating precipitating electrons carrying upward field-aligned currents on closed field lines (see a review by Kan, 1982).

The convection pattern or the large-scale electrodynamics undergoes a fundamental change following a northward turning of the IMF. During a prolonged northward IMF ($\gtrsim$ 1 hour), convection in the summer polar cap frequently exhibits the regular "four-cell" pattern, and sometimes the irregular "multi-cell" pattern (Maezawa, 1976; Burke et al., 1979; Horwitz and Akasofu, 1979; Burke et al., 1982; Burch et al., 1984; Reiff and Burch, 1984). The field-aligned current distribution in the polar cap changes systematically from a regular pattern on the dayside to an irregular pattern on the nightside of the dawn-dusk meridian. Assuming the ionospheric conductivity is uniform in the summer polar cap, the field-aligned current density is proportional to the divergence of the convection electric field. Therefore, there is a one-to-one correspondence between the field-aligned current pattern and the convection pattern. On this basis, the regular current pattern observed on the dayside of the dawn-dusk meridian is consistent with the four-cell convection pattern. The irregular field-aligned current pattern on the nightside of the polar cap can be indentified with the multi-cell convection pattern. This inference suggests that the multi-cell convection pattern observed in the summer polar cap should probably occur on the nightside of the dawn-dusk meridian. On the other hand, the convection pattern and the field-aligned current distribution in the winter polar cap are found to be always highly irregular and the ionospheric conductivity is as low as 0.1 mho (Burke et al., 1982; Iijima et al., 1984).

The polar cap potential decreases systematically with a northward turning of the IMF and reaches an asymptotic value of ~ 20 kV when $B_z > 0$ persists for several hours (Wygant et al., 1983; Reiff et al., 1981; Doyle and Burke, 1983). The asymptotic polar cap potential during prolonged northward IMF has been attributed to the viscous interaction between the solar wind and the magnetosphere.

Theoretical models of polar cap arcs are still in a very early stage of development. Burke et al. (1982) proposed a model in which polar cap arcs occur on open field lines subject to the $\vec{\nabla} \cdot \vec{E} < 0$ criterion (Lyons, 1980). To understand the cause of polar cap arcs, one needs a model of magnetospheric convection during northward IMF. Several such models of magnetospheric convection have been proposed based on (i) reconnections on the poleward side of the cusp region (Russell, 1972; Crooker, 1979; Maezawa, 1979; McDiarmid et al., 1980; Cowley, 1980; Burch et al., 1984; Reiff and Burch, 1984) and (ii) vacuum superposition of IMF and geomagnetic field (Cowley, 1973; Akasofu and Roederer, 1983; Lyons, 1984).

This paper is an attempt to bring together observational results and theoretical ideas, some of them have already been published, to form a working model for the polar cap arc during a prolonged period of northward IMF. The main issues to be addressed are to identify (i) the convection model and (ii) the energy source for the polar cap arc under the assumption of cusp reconnection during northward IMF.

2. Requirements of the convection model during northward IMF

Following a northward turning of IMF, possible configurations of the magnetosphere under the assumption of cusp reconnection have been summarized topologically by Cowley (1980).

Figure 1 shows (A) an initial non-steady configuration and (B) a final steady configuration of the magnetosphere during northward IMF. In the initial stage, field line 1-1' in Figure 1(A) convects in such a way that the convection electric field changes sign along the field line. This type of convection can be realized by a pair of oppositely propagating Alfvén waves. When a steady state is reached, Alfvén waves die out or turn into a standing field line structure so that the convection electric field do not change sign along a field line as is the case in Figure 1(B). In this connection, it may be noted that the polar cap arc model proposed by Burke et al., (1982) is not a valid steady-state model because it requires a reversal of the electric field along field lines passing through polar cap arcs.

The requirement on the convection model during northward IMF can be enumerated as follows:

(a) Alfvén waves are required to produce the dynamics for the transition from an initial state to a final steady state following a northward turning of IMF.

(b) Convection electric field cannot change sign along a field line in a steady state model.

(c) Convection cells in the polar cap are initiated near the cusp region following a northward turning of IMF and gradually extends nightside

(d) The polar cap potential decreases in time following a northward turning of IMF (e.g., Wygant et al., 1983). This means that the magnetosphere evolves towards a closed configuration, i.e., the memory of southward B_z is fading.

(e) Cusp reconnections are most likely asymmetric in the two hemispheres due to the tilting of earth's dipole axis and the azimuthal component (By) of IMF.

(f) Magnetosphere cannot be completely closed as long as IMF is nonzero and cusp reconnections are asymmetric which generates open field lines, see Figure 1(B).

(g) The convection model must be able to account for the sunward polar cap convection on closed field lines in a steady state which is closely associated with the bifurcation of the plasma sheet (Frank et al., 1982)

(h) Reconnection in the plasma sheet during northward IMF must take place away from the central channel around the noon-midnight meridian where the convection in the plasma sheet must be tailward to allow sunward convection in the polar cap. In this connection, it may be noted that the convection described in the model proposed by Burch et al. (1984) and, Reiff and Burch (1984) cannot proceed in a steady state.

3. A convection model and the dynamo region for the polar cap arcs

The requirements outlined in Section 2 are satisfied by the magnetospheric configurations in Figure 1, the convection pattern in the plasma sheet depicted in Figure 2 and the corresponding convection pattern in the ionospheric polar cap shown in Figure 3.

In Figure 2 the solid curve (with arrows) denotes convection pattern of closed field lines; the dashed curve (with arrows) denotes the convection of open field lines projected on the plasma sheet. Reconnection in the plasma sheet takes place where the dashed curve turns into solid curve near the flanks of the plasma sheet, leaving the central channel for the tailward convection of closed field lines. The wavy pattern in the convection pattern can result from the interchange instability on closed field lines. This instability can be driven by the curvature force (e.g., Krall and

Trivelpieces, 1973). Field line curvature favoring interchange instability do exist in the plasma sheet. The stabilizing force for this instability in the linear regime comes from discharging effect (or the line-tying effect, or short-circuiting effect) of the conducting ionosphere. Therefore low ionospheric conductivity is a favorable condition for the instability to occur. Further study is required to determine whether or not this instability can lead to the irregular multi-cell convection pattern observed preferentially in the winter polar cap and perhaps also on the nightside of the summer polar cap (see Figure 3).

The ionospheric electric field across the dawn-dusk meridian is shown in the middle panel of Figure 3. The field-aligned current pattern (under the assumption of an isotropic and uniform ionospheric conductivity) is depcited in the bottom panel of Figure 3. Also shown are the expected locations of the polar cap arcs, the oval arcs and the patchy auroras. The electron number density on open field lines (~ 0.1 cm^{-3} in the tail lobe) is typically one order of magnitude smaller than the density on closed field lines (~ 1 cm^{-3} in the plasma sheet and its boundary layer). In this connection we can expect the polar rain (Winningham and Heikkila, 1974; Hardy et al., 1982) to be on open field lines in the shaded region in Figure 3. The sunward convection in the central polar cap is on closed field lines with the electron number density significantly greater than that of the polar rain. The observed precipitation pattern appears to be consistent with the electron number density distribution based on the open and closed field line classification (Hardy et al., 1982). It is also consistent with the observation that the theta aurora appears to be on closed field lines (Peterson and Shelley, 1984). Under the assumption that auroral arcs must be located on the upward field-aligned current region, it is possible that the intense theta aurora occur on closed field lines while the less intense polar cap arcs may occur on either closed or open field lines. The difference in intensity between the theta aurora and the ordinary polar cap arcs can be attributed to the difference in number density and/or the acceleration potential of the precipitating auroral electrons.

The direction of the convection field $\vec{E}$, the cross-tail plasma sheet current $\vec{J}_o$ and the field-aligned current $\vec{J}_\parallel$ are also shown in the top panel of Figure 2. Note that the sense of $J_\parallel$ in Figure 2 is consistent with that shown in Figure 3. The dynamo region for the polar cap arcs in the plasma sheet is located where the convection is tailward and $\vec{E} \cdot \vec{J}$ is negative as indicated in Figure 2.

The current $\vec{J}_\perp$ in the plasma sheet can be written from the standard MHD momentum equation (i.e., Bostrom, 1974) as

$$\vec{J}_\perp = \frac{\vec{B}}{B^2} \times [\rho \ (\vec{V} \cdot \vec{\nabla}) \ \vec{V} + \vec{\nabla} p - \mu \ \nabla^2 \ \vec{V}] = \vec{J}_V + \vec{J}_p + \vec{J}_\mu \qquad (1)$$

where $\vec{J}_V$ is the current driven by $\rho(\vec{V} \cdot \vec{\nabla})\vec{V}$ the inertia force, $\vec{J}_p$ is driven by $\vec{\nabla} p$ the pressure gradient force and $\vec{J}_\mu$ is driven by $\mu\nabla^2 \vec{V}$ the viscous force. It should be emphasized that $\vec{J}_p$ is likely the dominant current near the inner-edge of the plasma sheet where the pressure gradient controls the plasma dynamics. The inertia current $\vec{J}_V$ is likely the dominant current in the near-earth and distant plasma sheet where the inertia force of plasma convection is expected to be greater than the plasma pressure force. The viscous current J_μ may play an important role in the low-latitude boundary layer. The divergence of field-aligned currents, neglecting the viscosity terms, can be written as

$$\vec{\nabla} \cdot \vec{J}_{\parallel} = - \vec{\nabla} \cdot \vec{J}_{\perp} = 2 \frac{\vec{J}_{\perp}}{B^2} \cdot (\vec{B} \cdot \vec{\nabla})\vec{B} + \frac{\vec{B}}{B^2} \cdot \vec{\nabla} \times [\rho \, (\vec{V} \cdot \vec{\nabla}) \, \vec{V}] \tag{2}$$

The dynamo region for the polar cap arc in our model is located in the distant plasma sheet near midnight meridian as indicated in Figure 2. Since the inertia is the dominant force in the distant plasma sheet, we expect that the field-aligned currents connected to the polar cap arcs are generated primarily by the inertia force in the second term of (2).

The inertia force given by the second term in (2) can contribute to the field-aligned current pattern shown in Figures 2 and 3 provided that the inertia force $\vec{F}_v$ is sheared across the plasma sheet as shown in the bottom panel of Figure 2. The required shear in $\vec{F}_v$ is consistent with the velocity shear of the convection pattern and the deceleration of convection due to the ionospheric loading effect (e.g., Kan, 1982) as shown in the middle panel of Figure 2. The current $\vec{J}_v$ and the electric field $\vec{E}$ as shown in Figure 2 are antiparallel to each other around the midnight meridian which constitutes a dynamo region ($\vec{J}_{\perp} \cdot \vec{E} < 0$) in the plasma sheet for the polar cap arc on closed field lines.

The scale lengths of the convection velocity shear required to drive the field aligned currents can be estimated from (2) (neglecting the first term) as

$$L_x L_y \simeq \frac{\rho \, V^2}{2 \, B_e} \left(\frac{B_i}{B_e}\right) \frac{L_c}{J_{\parallel i}} \tag{3}$$

Where L_x and L_y are the scale lengths of the convection velocity in the solar-magnetospheric coordinates (x axis is along the sun-earth line, y axis is perpendicular to the x axis and parallel to the ecliptic plane), B_i and B_e are the field magnitudes in the ionosphere and the equatorial plasma sheet respectively, L_c is the thickness of the eauatorial current sheet embedded in the plasma sheet, $J_{\parallel i}$ is the field-aligned current density at the ionospheric altitude, ρ is the mass density and v is the convection speed in the plasma sheet. As an example, we take the electric field $E_i(max) \sim 120$ mV/m,$J_{\parallel i} \sim 2\mu$ A/m^{2}as representative in polar cap arcs (Burke et al., 1982). For a polar cap arc of inverted-V scale, the width of the arc $L_a \sim 100$ km which maps into the plasma sheet to give

$$L_y = L_a \sqrt{\frac{B_i}{B_e}} \simeq 2\ R_E \qquad (4)$$

if $B_i = 3 \times 10^4\ \gamma$ and $B_e = 2\ \gamma$. Note that the orientation of polar cap arc is sun-aligned so that the width is measured by L_y. For $L_c = 3\ R_E$, $\rho = 8.4 \times 10^{-22}$ kg/m^3 ($n = 0.5$ cm^{-3} for a hydrogen plasma), $V = 400$ km/sec (corresponding to $v_i = 4$ km/sec or $E_i = 120$ mV/m). Substituting these parameter values into (3), one obtains

$$L_x \simeq 63\ R_E \qquad (5)$$

This means that the convection velocity scale length along the tail required to produce the field-aligned current density in a polar cap arc is on the order of tens of earth radii which is not unreasonable as far as convection in the plasma sheet is concerned.

Figure 4 is a schematic diagram of the dynamo region in the plasma sheet coupled to the central polar cap ionosphere. The equipotential contours in the upward field-aligned current region are shown by the dashed curves. The origin of the auroral acceleration potential in our polar cap arc model is identical to that of the oval arcs, and therefore will not be repeated here (e.g., Knight, 1973; Fridman and Lemaire, 1980; Lyons, 1980; Kan and Lee, 1980 and a review by Kan, 1982). Note that the S-shaped equipotential contours are on closed field lines where the theta aurora can be expected to occur. On the other hand, the V-shaped equipotential contours are partially on open field lines where the less intense polar cap arcs can be expected. This does not exclude the occurrence of the less intense polar cap arcs on closed field lines.

4. Summary

We have presented a working model of the polar cap arc during northward IMF. In the proposed model the polar cap arcs can be expected to occur preferentially on the dawnside of the polar cap. The theta aurora can be expected to occur on the closed field lines convecting sunward in the central polar cap while the less intense polar cap arcs can occur on either closed or open field lines. The dynamo region for the polar cap arcs is located in the central plasma sheet convecting tailward. The dynamo is driven by the inertia force of the plasma sheet convection which is in turn driven by the cusp reconnection, in contrast to the oval arcs during northward IMF which are powered by the viscous interaction in the low-latitude boundary layer.

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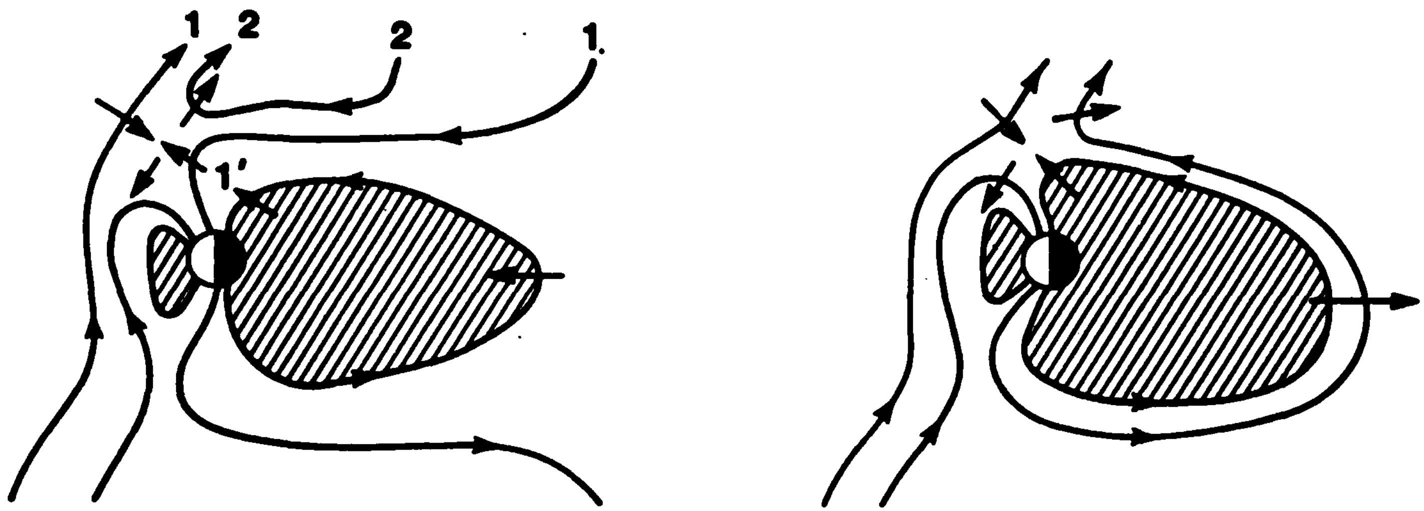
Figure Captions

Figure 1. Reconnection configurations during northward IMF. (A) Configuration during the initial transient stage following a northward turning of IMF. Note that the reconnection in the polar cusp region is assumed asymmetric in the two hemispheres. (B) The configuration of a final steady state due to dayside reconnection in the cusp region and nightside reconnection in the plasma sheet.

Figure 2. Convection pattern in the equatorial plasma sheet (top panel). The dynamo region for the polar cap arcs on closed field lines are located in the plasma sheet in the tailward convection region around the noon-midnight meridian. The required flow speed across the plasma sheet is shown in the middle panel. The bottom panel shows the resulting inertial force pattern which is required to produce the field-aligned current pattern as indicated in the top panel.

Figure 3. Ionospheric convection pattern (top panel) during a prolonged northward IMF. The polar cap is delineated by the dot-dashed curve. The shaded region is the open field line region. The dawn-dusk electric field pattern and the corresponding field-aligned current pattern (assuming a uniform ionospheric conductivity) are shown in the middle and bottom panels. The expected locations of the polar cap arcs, oval arcs and patch auroras are also indicated with reference to the field-aligned current pattern.

Figure 4. A schematic diagram illustrating the dynamo region in the plasma sheet, the field-aligned current and the equipotential contours (dashed curves) for the formation of the polar cap arcs.



(A)

(B)

Fig. 1

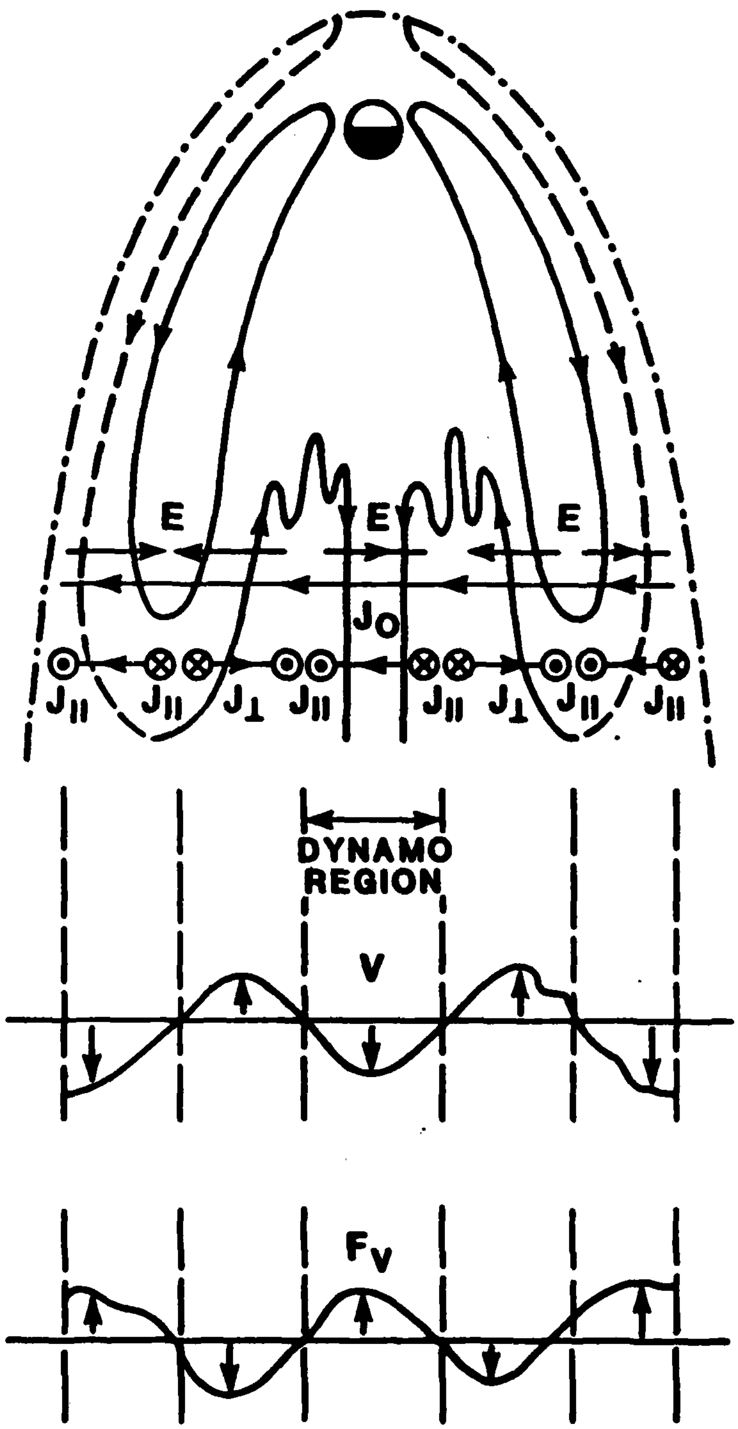
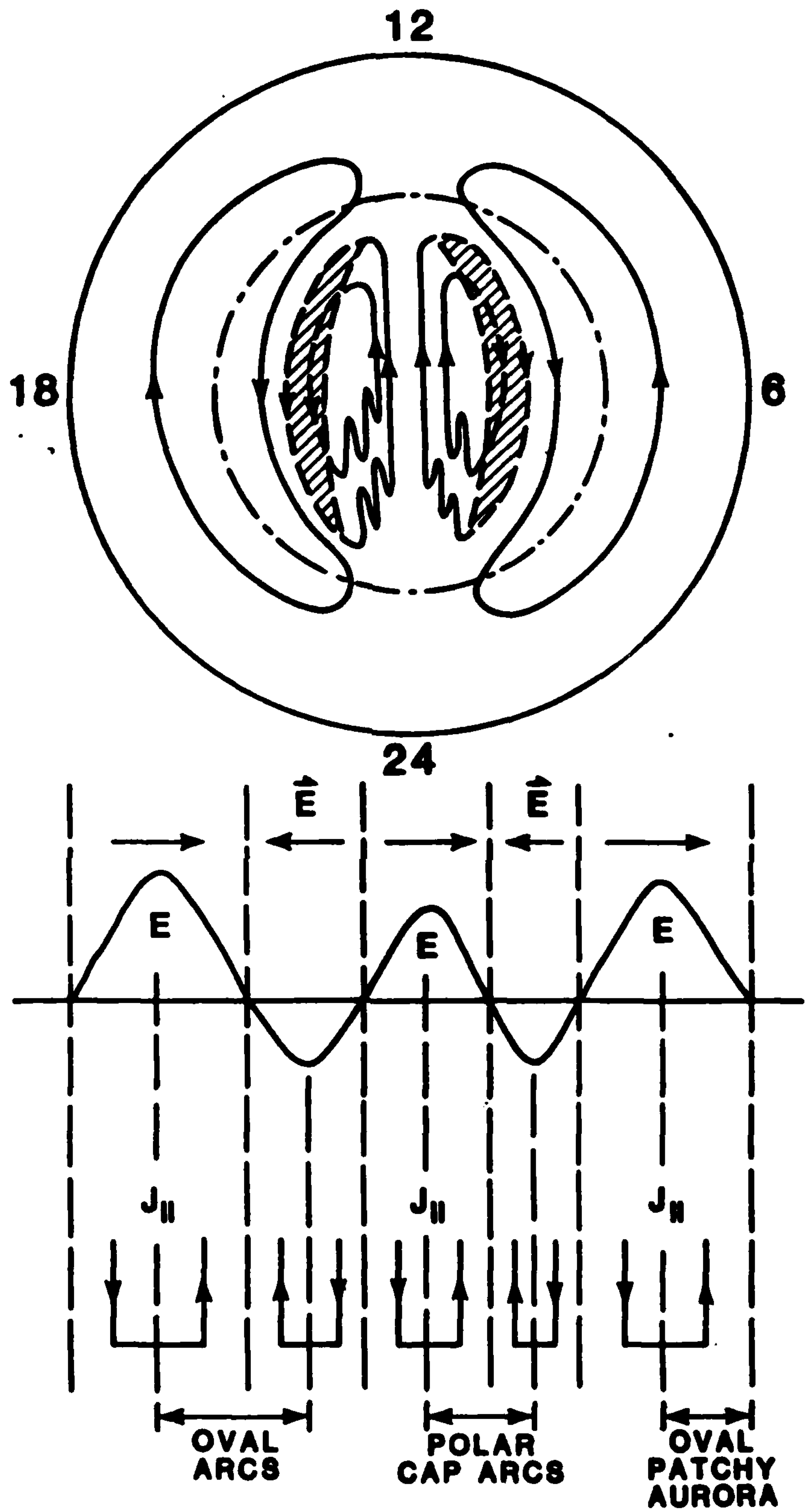


Fig. 2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$J_{\parallel}$
OVAL ARCS
POLAR CAP ARCS
OVAL PATCHY AURORA

Fig. 3

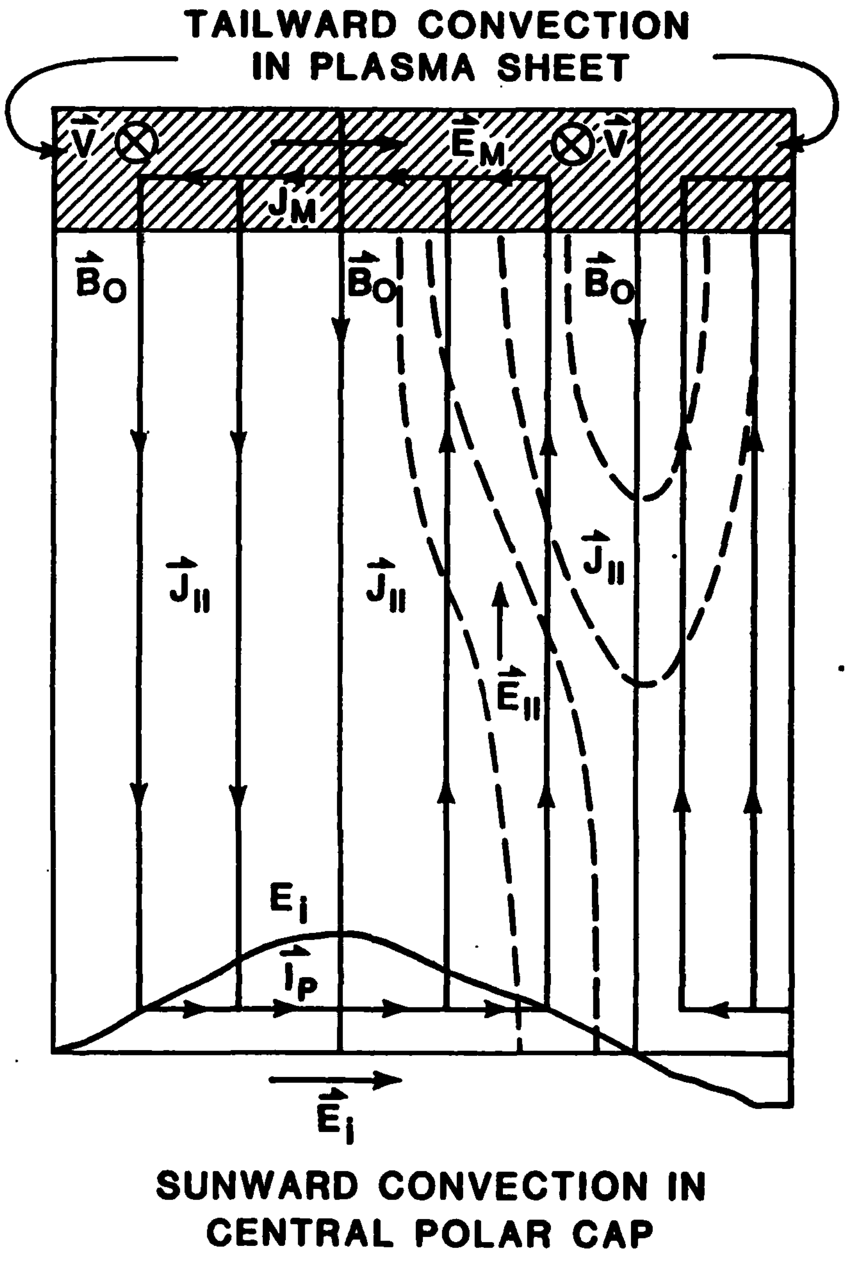
TAILWARD CONVECTION
IN PLASMA SHEET
$\vec{V}$
$\vec{E}_M$
$\vec{V}$
$\vec{J}_M$
$\vec{B}_O$
$\vec{B}_O$
$\vec{B}_O$
$\vec{J}_\parallel$
$\vec{J}_\parallel$
$\vec{J}_\parallel$
$\vec{E}_\parallel$
E_i
$\vec{I}_P$
$\vec{E}_i$
SUNWARD CONVECTION IN
CENTRAL POLAR CAP

Fig. 4

END

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